Mode

REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-02-

0239

1. REPORT DATE *(DD-MM-YYYY)*
30-09-2001

2. REPORT TYPE
FINAL

3. DATES COVERED *(From - To)*
6/30/1998 – 6/30/2001

4. TITLE AND SUBTITLE
EXPERIMENT-BASED DEVELOPMENT OF PHENOMENOLOGICAL MISTUNING MODELS FOR BLADED DISKS

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-98-1-0057

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
CHRISTOPHE PIERRE, PRINCIPAL INVESTIGATOR
STEVEN L. CECCIO
MATTHEW P. CASTANIER
JOHN JUDGE

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
THE UNIVERSITY OF MICHIGAN
MECHANICAL ENGINEERING DEPT.
2250 G. G. BROWN BUILDING
ANN ARBOR, MI 48109-2125

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release;
distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The major objectives of this research were: (1) to demonstrate and quantify the high sensitivity of bladed disks to mistuning and, in particular, the occurrence of vibration localization phenomena and associated forced response amplitude increases, (2) to achieve an understanding of the various sources and physical mechanisms of mistuning for a typical bladed disk and to develop the corresponding models, and, (3) to utilize the mistuning models developed to identify the key physical parameters governing mistuning effects, and in particular, to explore the feasibility of intentional blade mistuning. The importance of the research stems from the fact that small, random blade mistuning has been shown to have the potential to dramatically increase the in-operation amplitudes and stresses of turbine blades.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		10	19b. TELEPHONE NUMBER *(include area code)*

20020816 042

Final Report to

Air Force Office of Scientific Research
Aerospace and Materials Science
Structural Mechanics

Grant No. F49620–98–1–0057

EXPERIMENT-BASED DEVELOPMENT OF PHENOMENOLOGICAL MISTUNING MODELS FOR BLADED DISKS

Christophe Pierre
Professor
Phone: (734) 936-0401 *FAX*: (734) 647-3170 *email*: pierre@umich.edu

Steven L. Ceccio
Associate Professor

Matthew P. Castanier
Asst. Research Scientist

John Judge
Graduate Student

Department of Mechanical Engineering
2250 G. G. Brown Building
The University of Michigan
Ann Arbor, MI 48109–2125

OBJECTIVES

The major objectives of this research were: (1) to demonstrate and quantify the high sensitivity of bladed disks to mistuning and, in particular, the occurrence of vibration localization phenomena and associated forced response amplitude increases, (2) to achieve an understanding of the various sources and physical mechanisms of mistuning for a typical bladed disk and to develop the corresponding models, and (3), to utilize the mistuning models developed to identify the key physical parameters governing mistuning effects, and in particular, to explore the feasibility of intentional blade mistuning.

The importance of the research stems from the fact that small, random blade mistuning has been shown to have the potential to dramatically increase the in-operation amplitudes and stresses of turbine blades. Thus, mistuning can lead to premature blade fatigue. In particular, mistuning effects are a major cause of **high cycle fatigue (HCF),** which is a major readiness and safety concern for the US Air Force, since it is estimated that 30% of Air Force jet engine maintenance costs and 57% of Air Force fighter jet engine safety mishaps are due to HCF.

By improving blade mistuning prediction and analysis, this research program helps make it possible to improve rotors in the early design stages before problems occur. Furthermore, more robust rotor designs are being sought by investigating the effectiveness and practical implementation of intentional mistuning. Ultimately, this research will lead to a significant increase in the efficiency, reliability, and safety of gas turbine engines by helping to reduce high cycle fatigue over the entire engine operating range.

EXPERIMENTAL SETUP

An advanced experimental facility has been established at the University of Michigan. This state-of-the-art facility, called the Turbomachinery Vibrations Laboratory (**Figure 1**), includes two optical measurement systems and a non-contact excitation system. The first measurement system is an Electronic Speckle Pattern Interferometry (ESPI) system for capturing full-field images of bladed disk vibration modes (**Figure 2**) and forced response patterns. The ESPI system is complemented by the second measurement system: a single point laser vibrometer for accurately measuring single-point displacement amplitudes and phases. The vibrometer is mounted on computer-controlled actuators for automated, precise positioning relative to the test specimen. An array of speakers provides non-contacting, acoustic excitation of rotor blades (see **Figure 3**). The speakers are driven by signals from phase-synchronized function generators, allowing traveling wave excitation, and a system of computer-controlled variable gain amplifiers allows precise calibration of speakers.

ANALYTICAL AND NUMERICAL MODELS

In addition to the experimental effort, there has been an extensive intentional mistuning investigation. Analytical studies of lumped-parameter models have provided better understanding of the underlying physics, while computational studies of simple, lumped-parameter models of rotors—as well as much more complex models of industrial rotors—were used to validate the analytical results, run parameter studies, and perform "numerical experiments."

The major thrusts of this research were synergistic. The numerical work was used to design experiments and to identify key phenomena requiring experimental investigation. In addition, the experiments were used to validate the analytical and computational models, as well as to provide direction for further development of the reduced order modeling techniques.

ACCOMPLISHMENTS AND NEW FINDINGS

The major experimental equipment in the Turbomachinery Vibrations Laboratory (see **Figure 1**) has been integrated into a computer-controlled system. Capabilities include

full-field, qualitative measurements of the vibration pattern of a rotor as well as quantitative measurements at discrete points. These capabilities complement each other to provide rapid and thorough analysis of the vibration behavior of the rotor being investigated. The experimental work is documented in **Publications 5–8**; a brief summary is provided here.

A 24-bladed disk (**Figure 2**) was manufactured for benchmark experimental work. This bladed disk was designed in collaboration with Dr. Charles Cross, Director of the Air Force Research Laboratory's Turbine Engine Fatigue Facility at Wright-Patterson Air Force Base. It features behavior similar to industrial rotors, but it was designed specifically for vibration testing, including bench tests at the University of Michigan and spin tests at the Turbine Engine Fatigue Facility. Furthermore, it has a geometry that is suited to precise manufacturing, and it was machined to the tightest possible tolerances in order to minimize unintended blade mistuning and provide a nearly perfectly tuned baseline. The extended, nodal-diameter modes shown in **Figure 2** are characteristic of a tuned rotor. Mistuning can be systematically added by attaching small masses to the tip of each blade.

A system of computer-controlled variable gain amplifiers was constructed to allow precise calibration of the speaker excitation system (**Figure 3**). Output from each channel of the phase-synchronized signal generators was adjusted to compensate for variations between individual speakers and between speaker responses at varying frequencies. The combination of precise phase and amplitude control of the excitation signals allows the speakers to deliver standing- or traveling-wave excitation in any harmonic pattern necessary.

A method was developed for experimentally identifying the mistuning pattern of a bladed disk from experimental measurements of the response of the entire rotor. This is crucial for the analysis of *blisks*, in which blades and disk are manufactured as a single piece, and thus cannot be separated to allow testing of blade characteristics individually. This method has been validated experimentally using the 24-bladed disk described above, by adding known mistuning to the blades and verifying that the method successfully identifies the mistuning pattern and amplitude. **Figure 4** shows the results of using the mistuning identification method when known mistuning has been added to three blades of the blisk: the identification results are compared to the expected results based on the known mistuning added and the small amount of mistuning identified in the original, unmodified blisk.

In addition to the experimental work listed above, there has been an active research effort in the area of intentional mistuning. Previous work in this project (**Publications 1 and 2**) has demonstrated that intentional mistuning could be implemented into the nominal design of rotors in order to mitigate the damaging effects of unavoidable random mistuning. Recent work (**Publications 3 and 4**) has focused on determining the underlying,

fundamental mechanisms that allow intentional mistuning to significantly reduce blade vibration amplitudes and stresses.

The dynamic response of a representative lumped-parameter model was examined in detail in **Publication 4**. The forced response results showed that blade vibration was significantly reduced for a rotor with an intentionally mistuned design, compared to the same rotor with a tuned nominal design. The free response showed that the mode shapes of a rotor with small, random mistuning tend to be somewhat localized, with each mode having a few dominant harmonic components. Thus, these modes are susceptible to being strongly excited by engine order excitation. In contrast, the mode shapes of a rotor with both random and intentional mistuning tend to be more severely localized; yet they are comprised of several harmonics, with no dominant harmonic components. Therefore, they are less likely to be strongly excited by engine order excitation.

These observations explain how intentional mistuning effectively decouples the blades of a rotor, so that the vibration energy cannot be drawn from low-response blades to high-response blades. Therefore, the blade amplitudes and stresses of an actual rotor (i.e., a randomly mistuned rotor subject to engine order excitation) tend to be much closer to those predicted for the idealized (tuned) rotor when the nominal design includes intentional mistuning.

PERSONNEL SUPPORTED

The following personnel were supported by and/or associated with this research program:

- Christophe Pierre, Professor
- Steven L. Ceccio, Associate Professor
- Matthew P. Castanier, Assistant Research Scientist
- John Judge, Graduate Student Research Assistant

All personnel listed above are employed by the Department of Mechanical Engineering at The University of Michigan.

PUBLICATIONS

1. Castanier, M. P. and Pierre, C., 1997, "Consideration on the Benefits of Intentional Mistuning for the Forced Response of Turbomachinery Rotors," *Analysis and Design Issues for Modern Aerospace Vehicles*, ASME publication AD vol. 55, pp. 419–425.
2. Castanier, M. P. and Pierre, C., 1998, "Investigation of the Combined Effects of Intentional and Random Mistuning on the Forced Response of Bladed Disks," *Proceedings of the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Cleveland, OH, July 1998.

3. Bladh, R., Castanier, M. P. and Pierre, C., 1999, "Models of Rotor Mistuning and the Prediction of Mistuned Blade Forced Response," *Proceedings of the 4th National Turbine Engine High Cycle Fatigue Conference*, Monterey, CA, February 1999.
4. Brewer, M. E., Castanier, M. P., and Pierre, C., 1999, "Effects of Harmonic Intentional Mistuning on the Free Response of Bladed Disks," *Proceedings of the 17th ASME Biennial Conference on Mechanical Vibration and Noise,* Las Vegas, NV, September 1999.
5. Pierre, C., Ceccio, S. L., and Judge, J., "Experimental Investigations of Mistuned Bladed Disk Vibration," *Proceedings of the 5th National Turbine Engine High Cycle Fatigue Conference,* Chandler, AZ, March 2000.
6. Judge, J., Pierre, C., and Mehmed, O., "Experimental Investigation of Mode Localization and Forced Response Amplitude Magnification for a Mistuned Bladed Disk," *Proceedings of the 45th ASME International Gas Turbine & Aeroengine Technical Congress, Exposition and Users Symposium*, Munich, Germany, May 2000. **Also:** *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 123, No. 4, pp. 940-950, October 2001.
7. Judge, J., Pierre, C., and Ceccio, S. L., "Identification of Mistuning in Blisks," *Proceedings of the 6th National Turbine Engine High Cycle Fatigue Conference,* Jacksonville, FL, March 2001.
8. Judge, J., Pierre, C., and Ceccio, S. L., "Experimental Validation of Mistuning Identification Techniques and Vibration Predictions in Bladed Disks," *Proceedings of the 2001 CEAS/AAIA/AIAE International Forum on Aeroelasticity and Structural Dynamics*, Madrid, Spain, June 2001.

INTERACTIONS AND TRANSITIONS

Participation/Presentations at Meetings and Conferences

The results from this research program have been presented at several major conferences, including

- The National Turbine Engine High Cycle Fatigue Conference
- The ASME International Gas Turbine & Aeroengine Technical Congress, Exposition, and Users Symposium
- The AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
- The ASME Biennial Conference on Mechanical Vibration and Noise
- The CEAS/AAIA/AIAE International Forum on Aeroelasticity and Structural Dynamics

A list of the papers presented at these conferences is included in the previous section of this report, entitled "PUBLICATIONS."

Consultative and Advisory Functions to Other Laboratories and Agencies

The investigators have worked closely with members of the Turbine Engine Fatigue Facility (TEFF) of the Air Force Research Laboratory at Wright-Patterson Air Force Base. In particular, the investigators collaborated with the director of TEFF, Dr. Charles Cross, in designing the new experimental blisk (**Figure 2**). The blisk was designed so that it is compatible with the dimensions and hardware of the spin rig at TEFF. Upon completion of the bench tests at The University of Michigan, a series of spin tests will be performed at TEFF.

In addition, the investigators have worked with Mr. Oral Mehmed of the NASA Glenn Research Center in designing the experiments for this research program. Mr. Mehmed is a co-author on a recent paper on the experimental work (**Publication 6**).

Transitions

An important part of the Turbomachinery Vibrations Laboratory is the laser vibrometer and the associated computer-controlled positioning system (see **Figure 1**). The vibrometer-positioning system was developed in this research program as a means of taking accurate measurements at precise locations on each blade of a rotor. This setup has proven to be very successful for collecting quantitative data, and it has been transitioned to the Air Force—a similar system is being installed at the Turbine Engine Fatigue Facility.

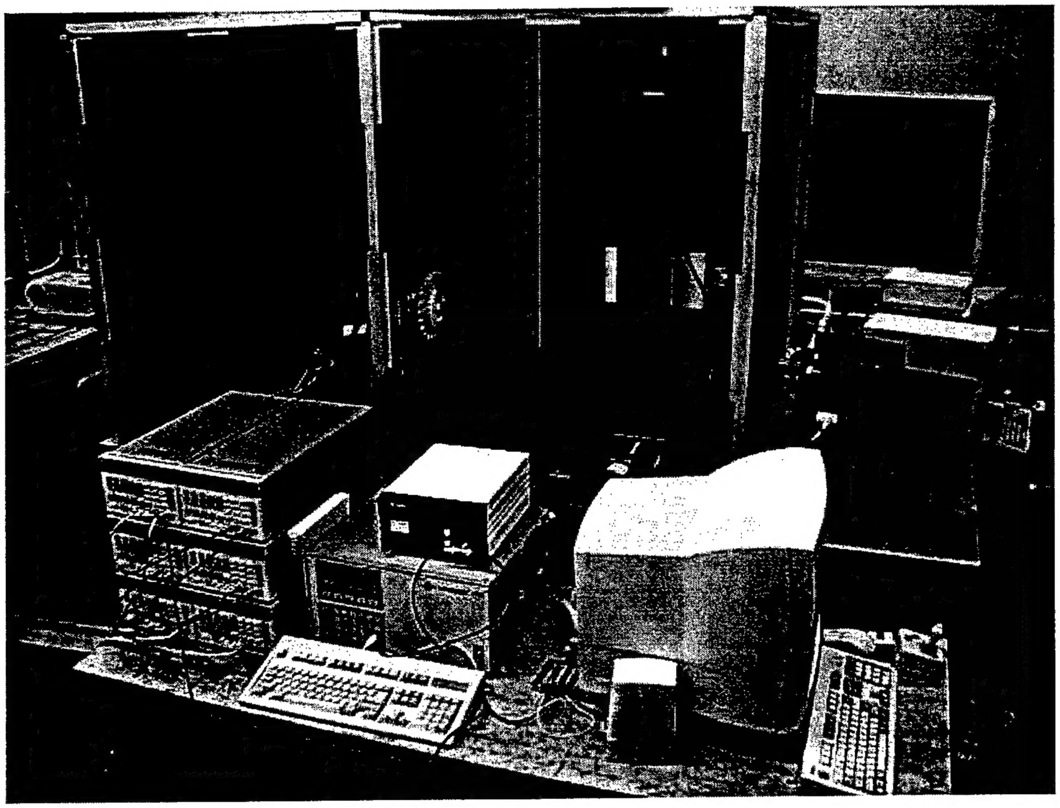

Figure 1: The Turbomachinery Vibrations Laboratory at the University of Michigan.

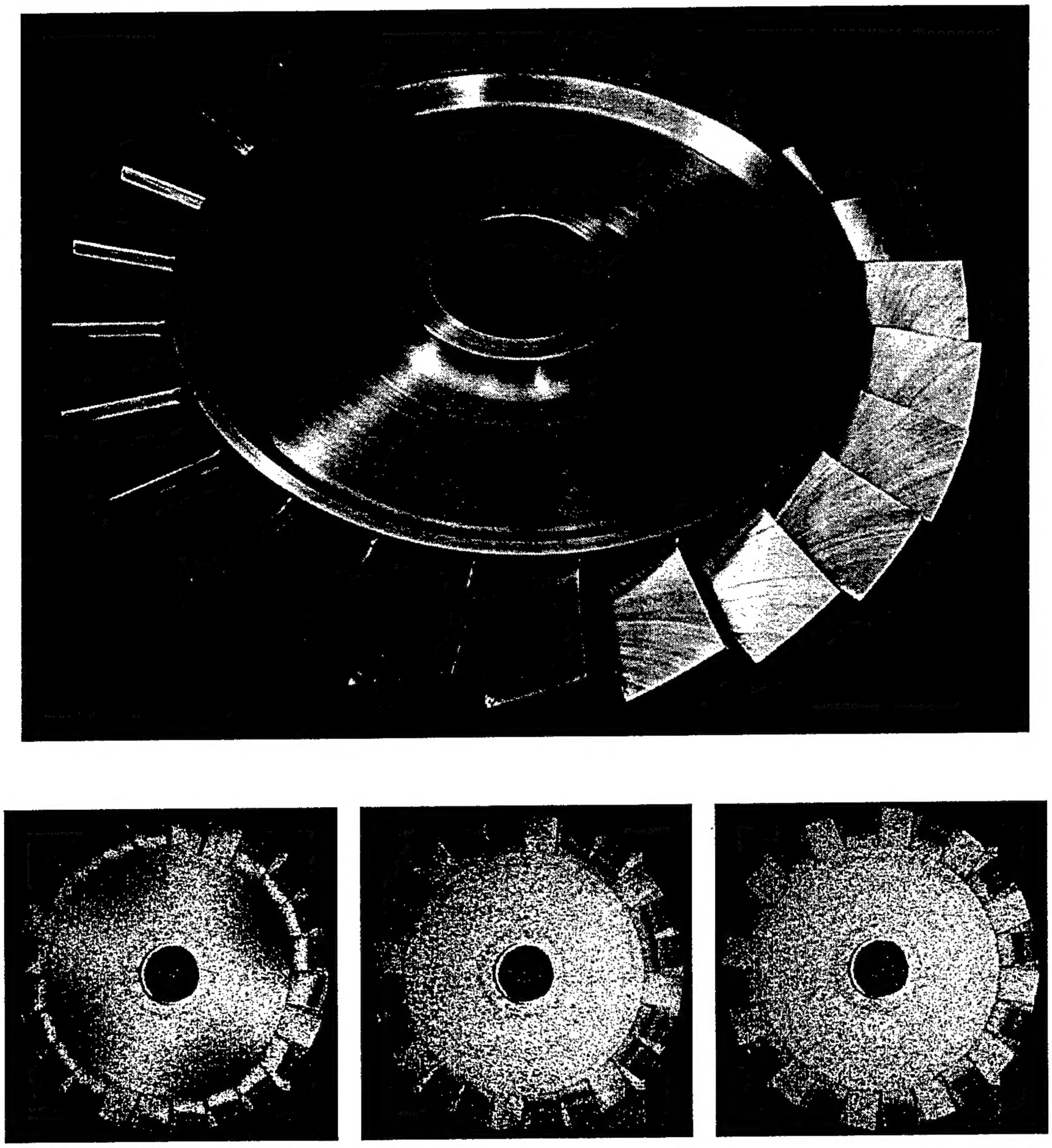

Figure 2: *Top:* The experimental bladed disk, which is also called the "validation blisk." *Bottom:* Images of mode shapes with 2 nodal diameters (left), 4 nodal diameters (center), and 6 nodal diameters (right).

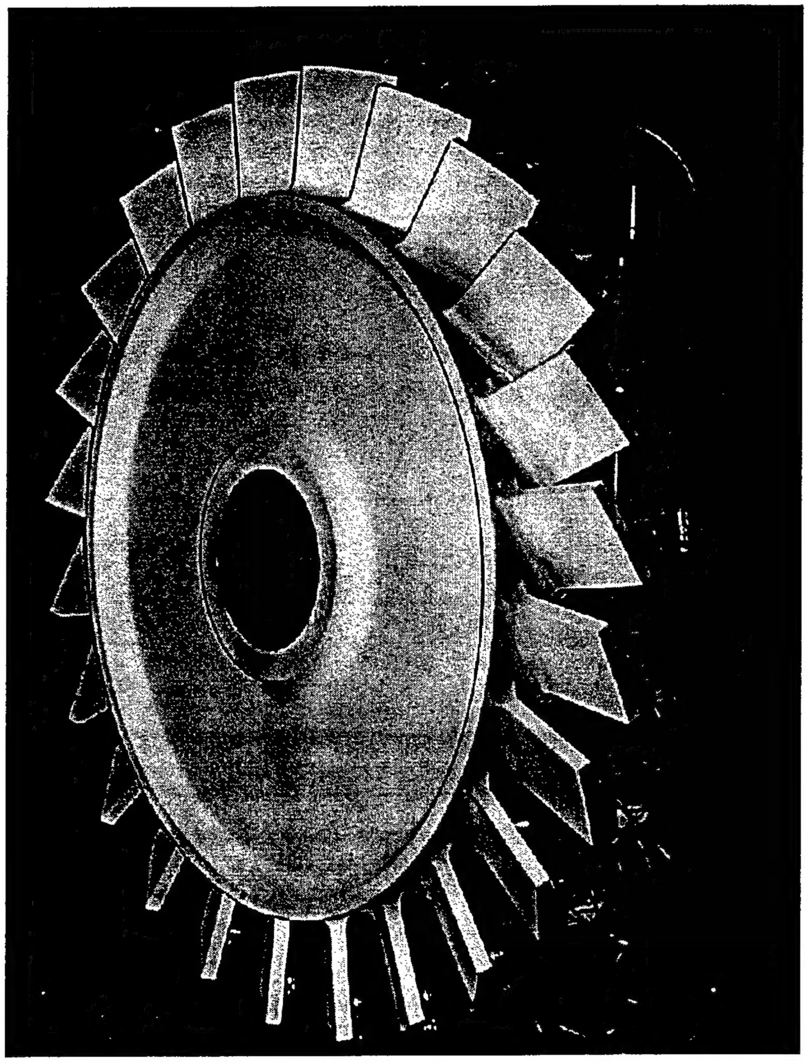

Figure 3: Validation blisk with acoustic excitation sources.

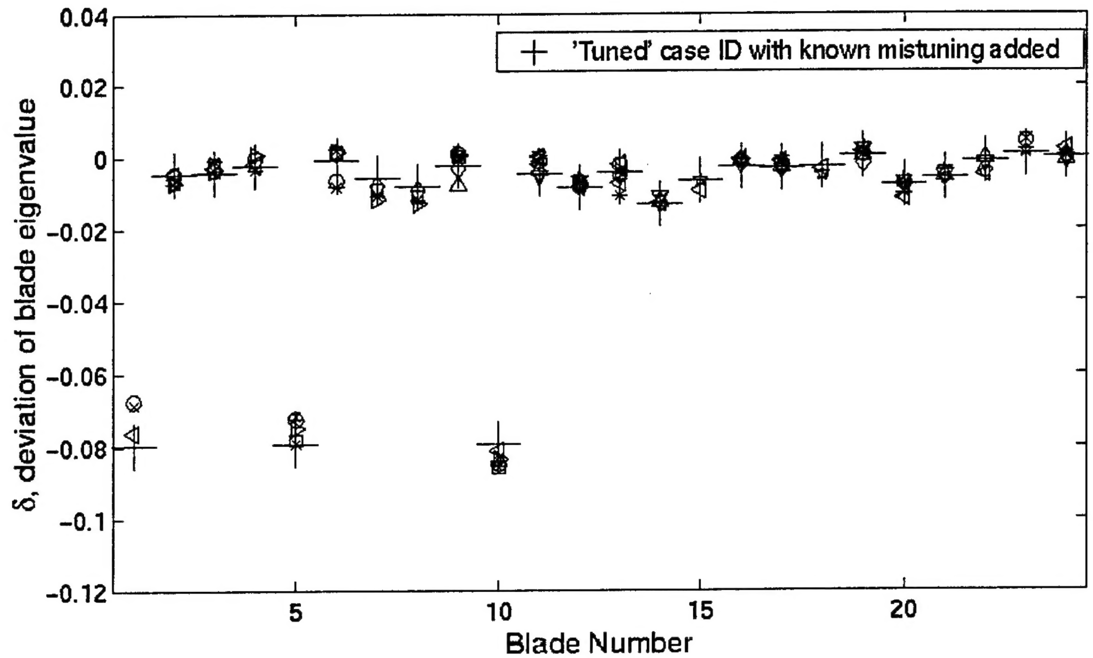

Figure 4: Mistuning identification results for the 24-blade validation blisk with known mistuning added to blades 1, 5, and 10. The crosses (+) show the "known" mistuning pattern, while the other symbols show mistuning patterns that were identified experimentally by measuring system mode shapes. It is seen that the mistuning identification technique performed well for this case.